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MHD models and synthetic synchrotron maps for the jet of M87

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We present a self-consistent MHD model for the jet of M87. The model consist of two distinct zones: an inner relativistic outflow, which we identify with the observed jet, and an outer cold disk-wind. While the former does not self-collimate efficiently due to its high effective inertia, the latter fulfills all the conditions for efficient collimation by the magneto-centrifugal mechanism. Given the right balance between the effective inertia of the inner flow and the collimation efficiency of the outer disk wind, the relativistic flow is magnetically confined into a well collimated beam for a wide range of parameters and matches the measurements of the opening angle of M87 over several orders of magnitude in spatial extent.

In the second part of this work, we present synthetic synchrotron emission maps for our MHD models. In principle the two-zone model can reproduce the morphological structure seen in radio observations, as central-peaked profiles across the jet close the the source, limb-bright further down the jet, and a bright knot close to the position of HST-1. However it is difficult to reconcile all features into a single set of parameters.

1. Introduction

Since its discovery by Curtis the jet of M87 is the classical prototype for extragalactic jets. Therefore, it is an ideal candidate for testing specific jet formation mechanisms. The jet and its hot spots have been systematically studied across the electromagnetic spectrum from the radio to X-rays, both, with ground-based observations and from satellites. The jet is clearly detected at mm wavelength with a resolution of 0.009 pc out to distances of about 2 mas from the core. The initial opening angle is approximately 60° on scales of about 0.04 pc and decreases rapidly until reaching 10° at a distance of 4 pc from the core [2]. These observations suggest, that the jet of M87 is rather slowly collimated across a length of several parsec.

The prevailing paradigm for jet formation and collimation is magnetic self-collimation by the Blandford & Payne process [3]. However, relativistic effects have been shown to decrease the collimation efficiency [4, 9]. Not only is the mass flux fraction very low, but the final opening angle is larger for relativistic outflows due to the decollimating effect of the electric field and the effective inertia of the plasma [5], which both counter-act the pinching by the toroidal magnetic field.

In a series of papers [6, 10, 11] tackled this problem and suggested a two-zone model. The model consists of an inner relativistic outflow, which is identified with the observed jet, and an outer non-relativistic disk-wind. [6] could show, that such two-zone models could easily account for the narrow appearance of the beam of extragalactic jets by reproducing the observational measurement of the opening angle distribution as a function of angular distance from the core as collected by [2].

In deriving the opening angle of their model, [6] made a simplifying but crucial assumption. They identified the observed jet with the inner relativistic outflow of their two-zone model. More specifically, the boundary of the jet was assumed to coincide with the shape of a specific fieldline Ψ_α separating the relativistic inner region from the non-relativistic outer disk-wind at the base, or the launching surface, of the outflow. So, the observed opening angle was strictly speaking fitted by the shape of a single magnetic fieldline.

From an observational point of view, the width of the jet is defined by the emission dropping below the detection limit or a small fraction of the luminosity of the ridge line of the jet. So the question is still, how well did [6] measure the width of the jet in terms of observational quantities?

The purpose of this paper is to answer exactly this question by adopting the point of view of an observer. Assuming, that the main radiation mechanism is synchrotron emission, we translate the MHD model into a synthetic emission map and measure the width of the jet using only this data.
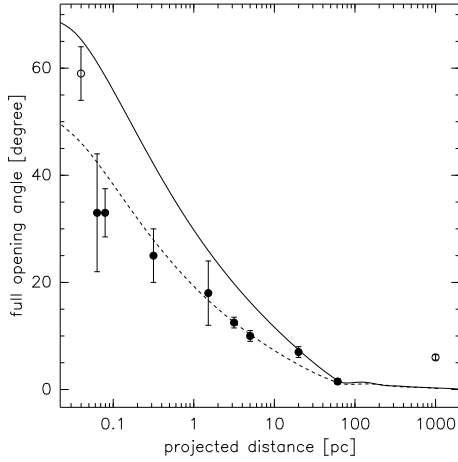
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Fig. 1.   Comparison of the opening angle calculated from model 1 (*solid lines*) and model 2 (*dashed line*), respectively, and the observational data for the jet of M87 (*data points*).
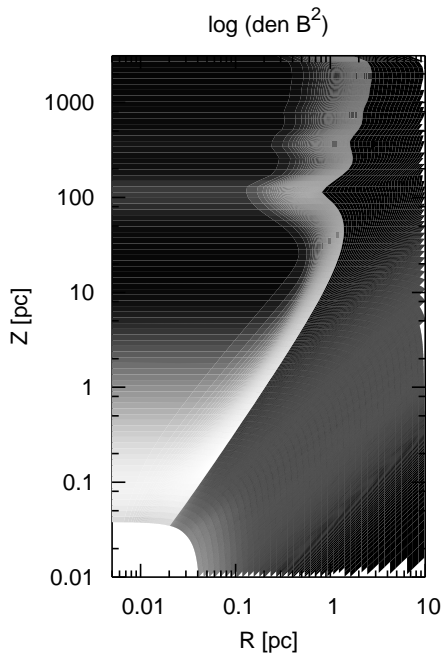

Fig. 2.   Estimate of synchrotron emissivity through $\rho\,B^2$ for model 1.

2. MHD model

We adopt the model and notation of [6] and refer the reader to that paper for details. There you will also find a schematic of the model in Fig. 4.

The model consist of two distinct zones, an inner outflow, which is dominated by relativistic dynamics, and an outer non-relativistic outflow. Both outflows originate from a spherical launching surface threaded by a radial magnetic field. The two zones are separated by a specific fieldline Ψ_α, where 2α is the initial angular width, or opening angle, of the inner relativistic outflow. We impose two different set of boundary conditions in the two distinct zone along the launching surface. Beyond the launching surface we solve the problem self-consistently, including the magnetic field structure, as a function of the boundary values alone.

This procedure yields a set of quantities as a function of space in the comoving frame of the jet. GBT05 used the shape of the separating fieldline Ψ_α to fit the observed opening angle as a function of distance from the core as collected by [2]. Unfortunately, the parameter space of the MHD model is degenerated in the sense, that very different set of parameters yield equally good fits or even almost identical opening angle distributions. Only 3-4 of the formally 7 parameters of the model seem to be independent.

Typically, models that fit the observed opening angle well are moderately relativistic, both in terms of the initial outflow velocity $\Gamma \sim 2$ and the initial plasma internal energy $T \sim 3mc^2$. The plasma velocity increases along the flow to values up to $\Gamma \sim 6-8$. However, the plasma may decelerate and reaccelerate sharply if recollimation takes place. Strong gradients of the plasma velocity may generally be present across the jet. It is therefore very difficult to assign a *typical* Lorentz factor to the jet.

In the following we discuss two exemplary models. We note however, that due to the degeneracy of the parameter space, each model could be realized by a range of formal parameter sets. Therefore, we will not give specific parameter values and designate them simply model 1 and model 2.

Figure 1 compares the opening angle as defined by the separating fieldline Ψ_α with the observational measurements. All our models fail to fit the jet width at large distances close to the optical knot A at $\sim$ 900pc [6]. Models with large initial opening angle, as model 1, have a hard time reproducing the opening angle distribution. It is in general very difficult to make the curve more concave. Models with initial opening angles falling slightly short of the measured value, as eg model 2, may easily reproduce the rest of the measurement and yield quite good fits. Note, that both models show a clear kink at $\sim 70\,\mathrm{pc}$. This is due to fact, that these jets, as most models, over-expand and are forced to recollimate towards the axis.
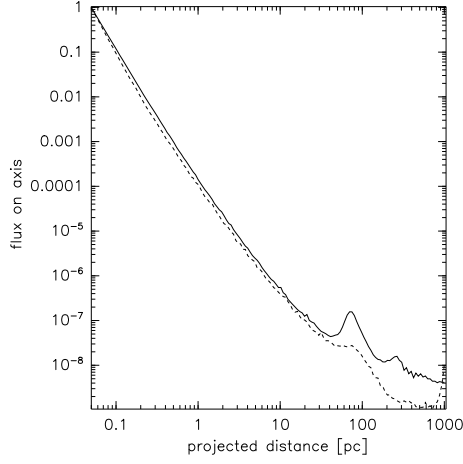
Fig. 3.   Comparison of the synchrotron flux along the jet axis calculated from model 1 (*solid lines*) and model 2 (*dashed lines*), respectively.
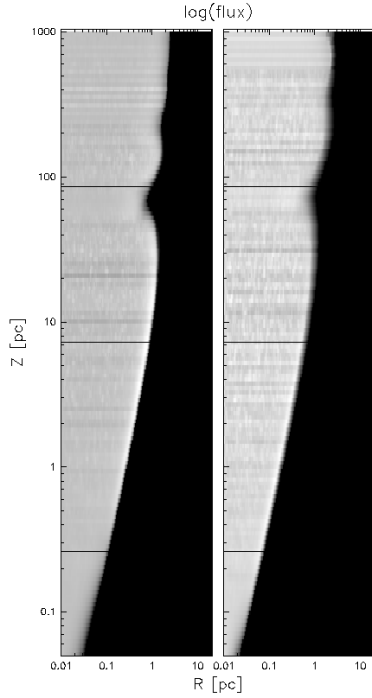

Fig. 4.   Synthetic synchrotron map for model 1 (*left panel*) and model 2 (*right panel*).

3. Synchrotron maps

The synthetic synchrotron emission maps shall qualitatively reproduce 1) opening angle defined through HWQM (half-width quarter-maximum), 2) bright knot at the position of HST-1 at projected
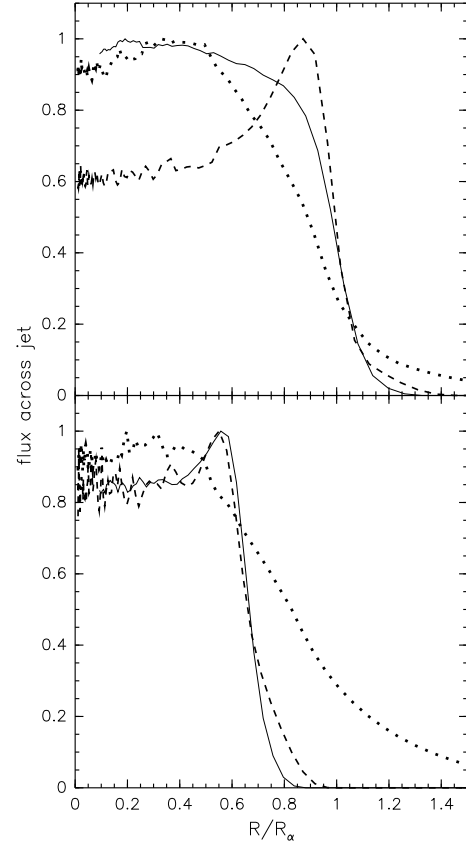

Fig. 5.   Comparison of the synchrotron flux across the jet beam calculated from model 1 (*upper panel*) and model 2 (*lower panel*). Each panel shows profiles across the jet beam at three different positions along the jet, ie close to the core (*thin solid line*), at intermediate distance (*dashed line*), and at large distance (*heavy dotted lines*). The lateral coordinate is normalized to the width of the jet R_α as defined by the dividing fieldline Ψ_α.

distance $\sim 70\,\mathrm{pc}$ 3) general morphology perpendicular to the jet axis, ie *limb-bright* far from the core and *center-bright* close to the source, 4) general trend along the axis $L_\nu \sim Z^{-1.5}$ [8].

For the moment the calculation of the radio emissivity ϵ is done following [7]. It is assumed, that the radiating region is optically thin with a uniform and isotropic distribution of electrons

$$N(E) \propto E^{-(2\alpha+1)} \qquad (1)$$

giving rise to radiation with spectral index α, ie. $S_\nu \propto \nu^{-\alpha}$ in the comoving frame.

If the radiating plasma moves at relativistic speeds, ie $\Gamma \gg 1$, the synchrotron emission has to be evaluated in the comoving frame Σ', instead of the lab- or observers frame Σ. The synchrotron emissivity in the comoving frame is given by the magnitude

of the magnetic field perpendicular to the line-of-sight and the electron density as $\epsilon' \propto \rho'|\vec{B}' \times \hat{n}'_{\text{los}}|^{\alpha+1}$, where $\rho', \vec{B}'$ and $\hat{n}'_{\text{los}}$ are the electron density, magnetic field and line-of-sight unit vector in the comoving frame, respectively.

The emissivity in the lab frame ϵ appears Doppler-boosted as $\epsilon = \mathcal{D}^{\alpha+2}\epsilon'$, with a Doppler factor $\mathcal{D} = (\Gamma(1 - \vec{v}\cdot\hat{n}_{\text{los}}/c))^{-1}$. Finally, the flux in the plane of the sky, I, is given by integration along the line-of-sight. The amount of relativistic beaming strongly depends on the line-of-sight angle, ie the angle between the jet axis and the direction to the observer, which we fix to $\theta_{\text{los}} = 40°$.

In the following we discuss the same two exemplary models as in the previous section. To this end, we plotted spatial 2-dimensional synthetic synchrotron emission maps (figure 4), the flux measured on the jet axis as a function of distance from the core (figure 3), and the flux profiles across the jet at various positions along the jet axis (figure 5).

Figure 3 illustrates the trend along the axis. Both models show similar power-law indices. However, the model jets dim out faster than the observed jet (power-law index ~ -2 versus -1.5). Further, both models show a sharp rise of luminosity around 70 pc, where the flux increases by more than an order of magnitude over the power-law. The location of this bright spot coincides with the location of strong recollimation shocks

Figure 4 shows synthetic synchrotron maps. In order to increase the contrast we divided the map by the trend along the jet axis. The jet beam is well defined, showing large opening angles close to the core and becoming almost conical a large distance. Both models show a strong decrease of the jet width forming a visible neck at the position of the recollimation shock.

The synthetic synchrotron maps show strong gradients of flux across the jet. These are more clearly visible in figure 5, were cuts across the jet are shown. For model 1 the profiles clearly show limb-brightening from distance ~ 0.5 pc to close to the neck in the jet. The regions close to the core and the neck are brightest on the jet axis, ie centrally-peaked. In the limb-bright region, the flux on axis can be as small as half the limb flux. Model 2 generally shows less variation of the flux across the jet. While close to the core the emission is still centrally-peaked, limb-brightening takes over much faster at ~ 0.2 pc but is not as prominent. The on-axis flux is $\sim 80\%$ of the limb.

4. Summary

The morphological structure across the jet can be reproduced in principle. A wide range of models show limb-brightening away from the core. However, this may be hidden due to projection and beaming effects for small line-of-sight angles.

Most models with acceptable fits to the opening angle distribution feature a recollimation shock at the distance of HST-1. Only models with very small initial opening angles do not seem to over-expand.

However, it is seem to be difficult to reconcile all observational constraints with a single set of parameters. So far, no model of our parameter study reproduces all features with high accuracy. This is particularly true for models with a line-of-sight angle $\theta_{\text{los}} = 20°$. it seems to be easier at larger angles $\theta_{\text{los}} = 40°$. Clearly this calls for a denser and wider coverage of the available parameter space.

Including of synchrotron total flux into the analysis in addition to the openening angle distribution does not completely break the degeneracy of the parameter space. Hopefully, extension to polarization measurements will improve the situation.

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